High Field Superconducting Magnets for Accelerators – Thinking outside the Box

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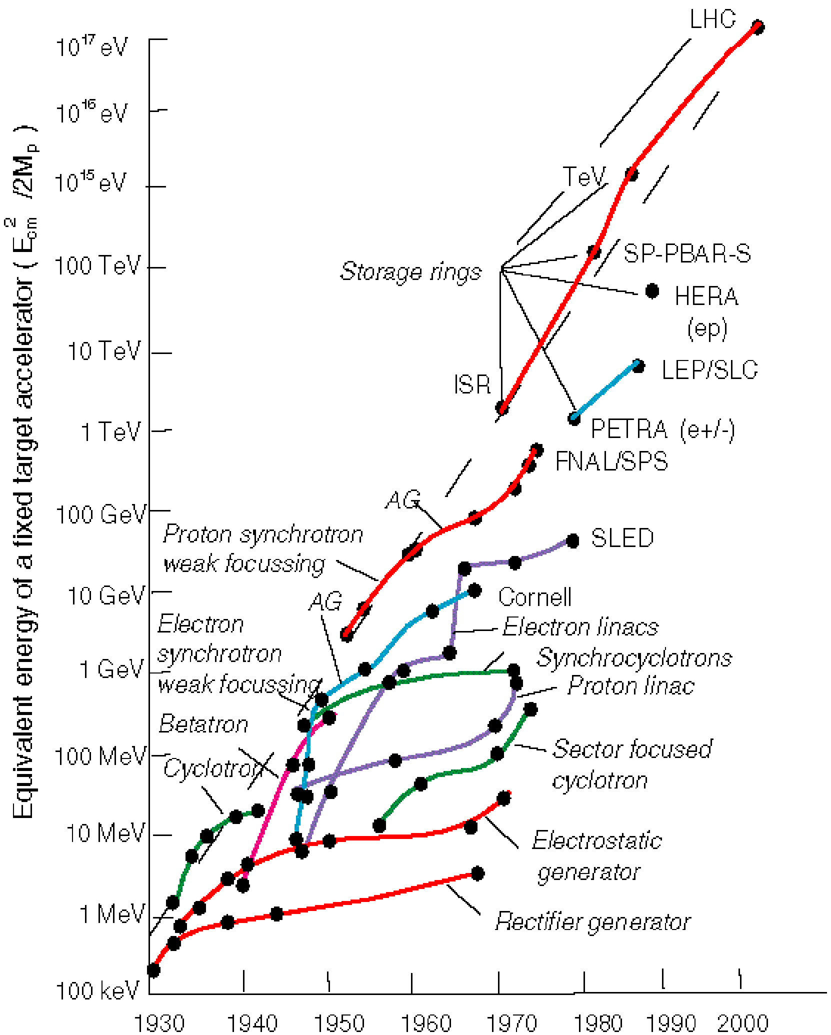
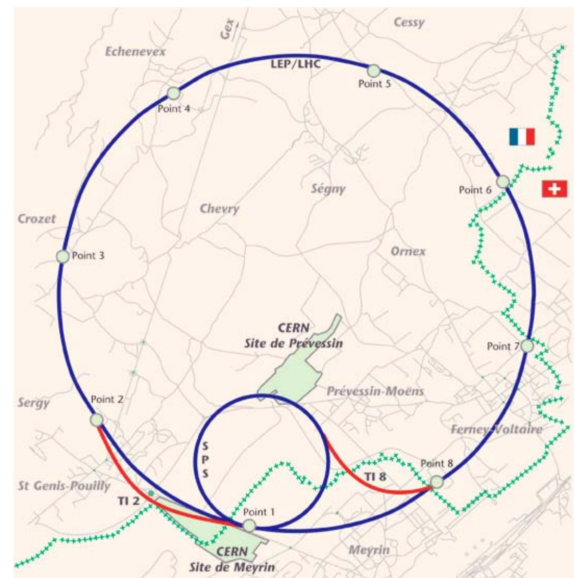
CERN

Erice Workshop, October 26 - 31, 2003

Accelerator Energy and Magnetic Field





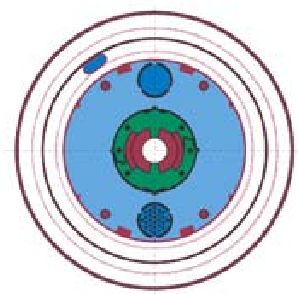
$F = q \cdot v \cdot B = mv^2 / \rho$

$$\mathbf{p = q \cdot \rho \cdot B}$$

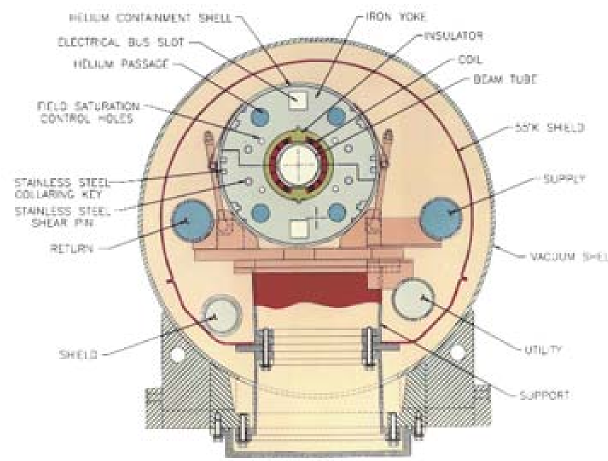
P [TeV/c] = 0.3 • ρ [km] • B[Tesla]

Large Radius and High Field

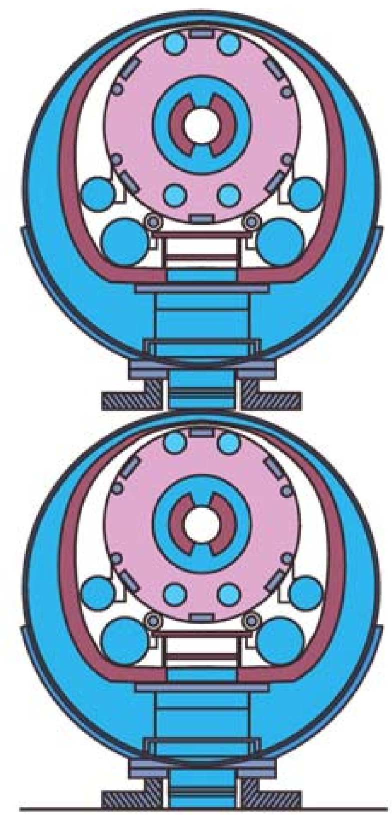
Dipole Magnets from 3 to 9 T



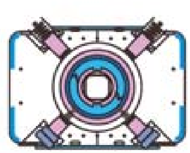
HERA
B = 4.7 T
BORE : 75 mm



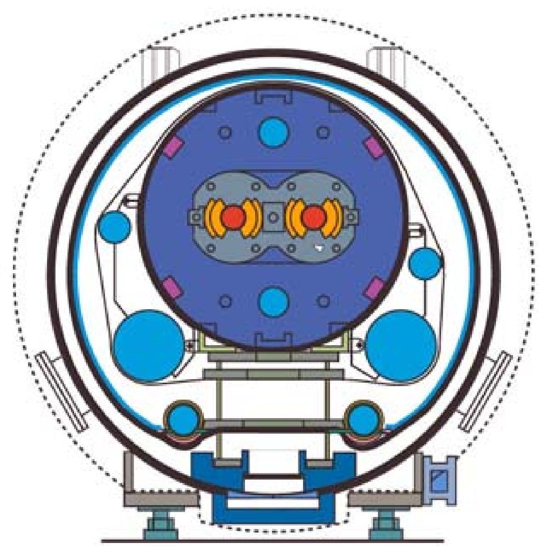
RHIC
B = 3.5 T
Bore : 80 mm



SSC
B = 6.6 T
Bore : 50-50 mm

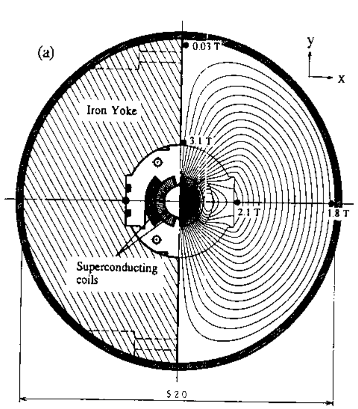


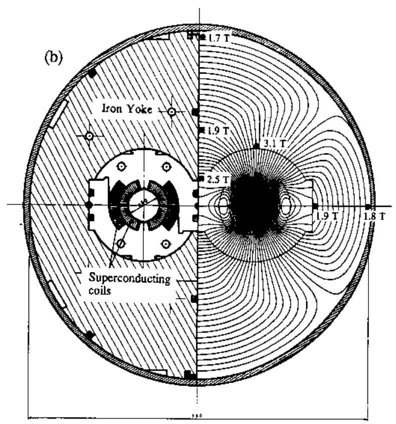
TEVATRON
B = 4.5 T
Bore : 76 mm

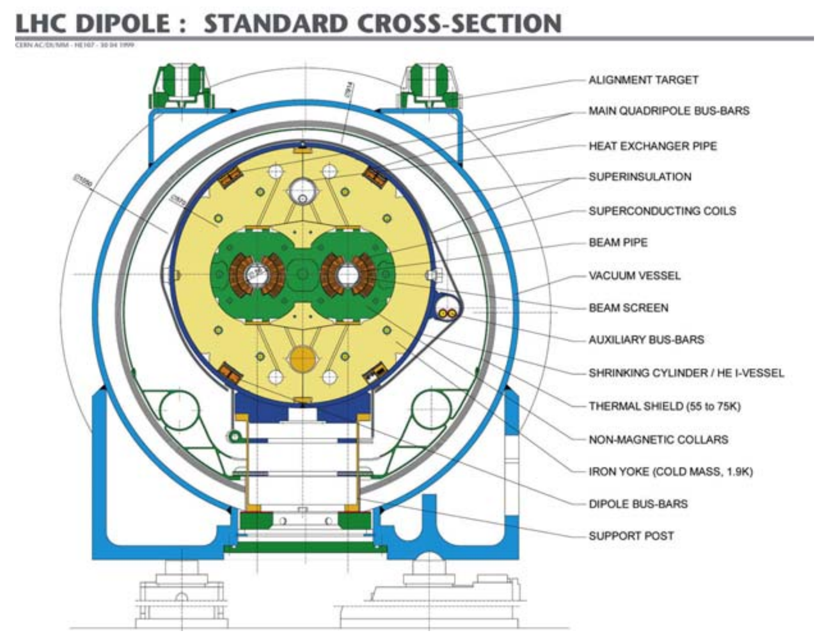


LHC
B = 8.3 T
Bore : 56 mm

LHC Twin Aperture Dipoles

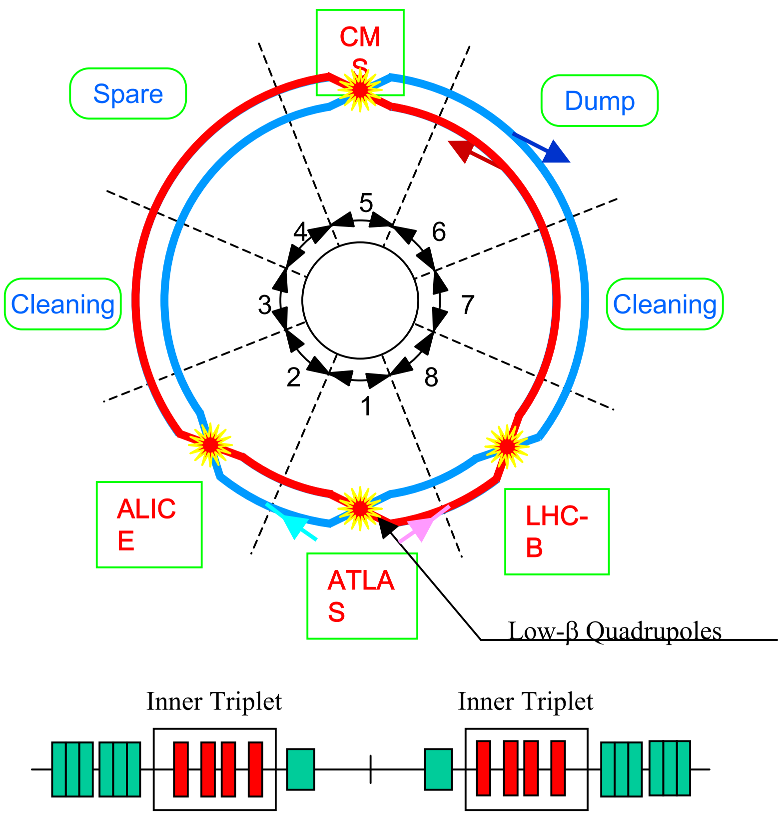


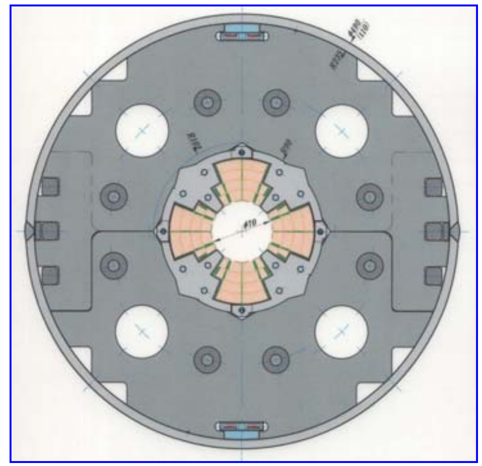


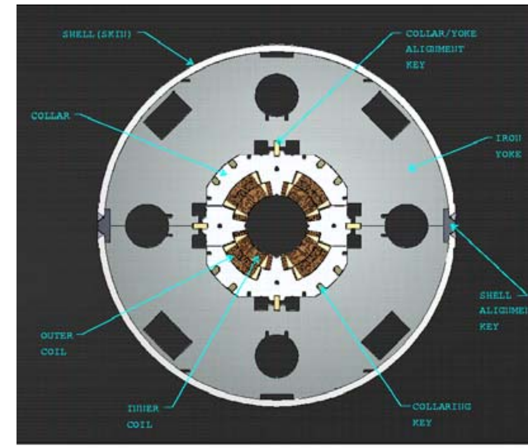


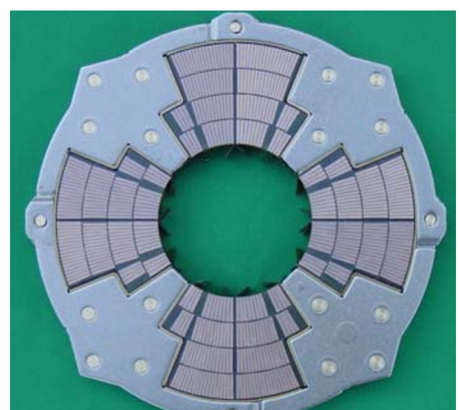
- Twin aperture: space saving, cost saving,
  (First proposed by John Blewett (BNL))

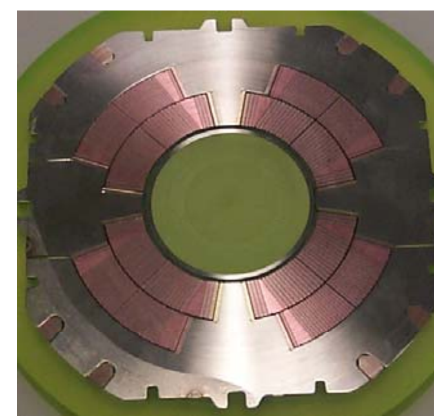
High Field Gradient Quadrupoles at Beam Interaction Regions









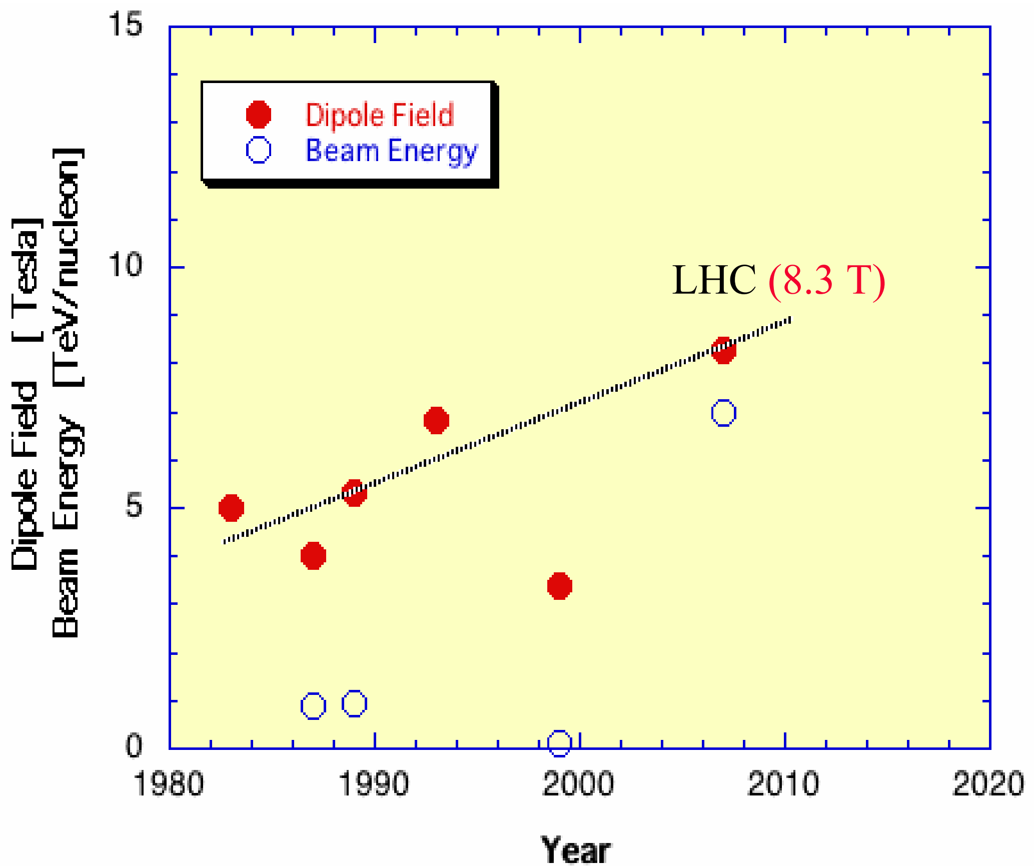


KEK

Fermilab

SC Accelerators and Dipole Field

	Energy [TeV/Beam]	Field Op. [Tesla]	Tunnel [km]	Status [year]
CBA	0.4	5	3.8	Cancelled (1983)
Teva-tron	0.9	4.4	6.3	Operated (1987)
HERA	0.92	4.7	6.3	Operated (1989)
SSC	20	6.8	87	Cancelled (1993)
RHIC	0.1	3.5	3.8	Operated (1999)
LHC	7	**8.3**	27	Operation (2007)



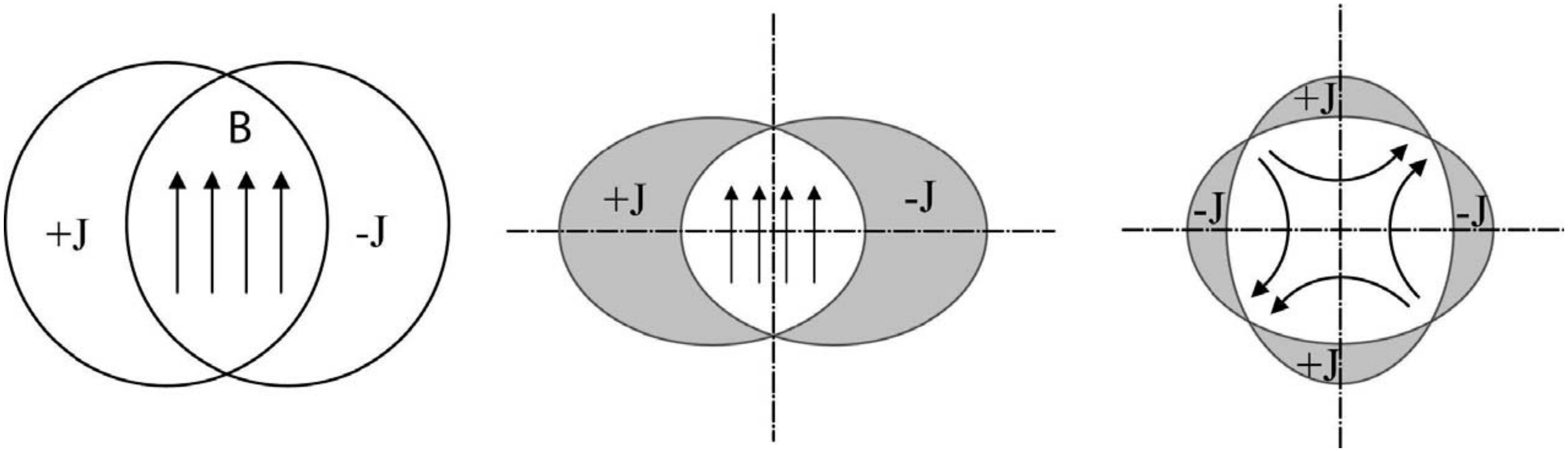
Comments

- Note the small size of the Tevatron magnet!

Scaling up the field and gradient in cold iron magnets will make them large and heavy.

We should not exclude a return to warm iron, or a combination of warm and cold iron

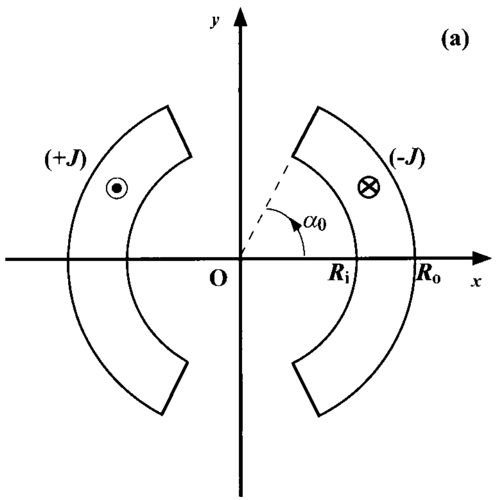
Dipole and Quadrupole Field Generated by Current Distribution



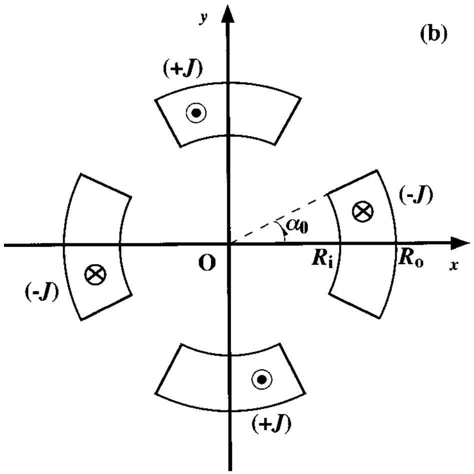
- A cylindrical cos $n\theta$ current distribution, where θ = azimuthal angle (as also given by superimposed ellipses) provides
  - Dipole ($n = 1$), quadrupole ($n = 2$) and Higher Order Multipole Fields
  - High current density is essentially required for higher field
  - Very precise field quality ($dB/B < 10^{-4}$) required for beam handling

Cosθ and Cos2θ Coil Designs

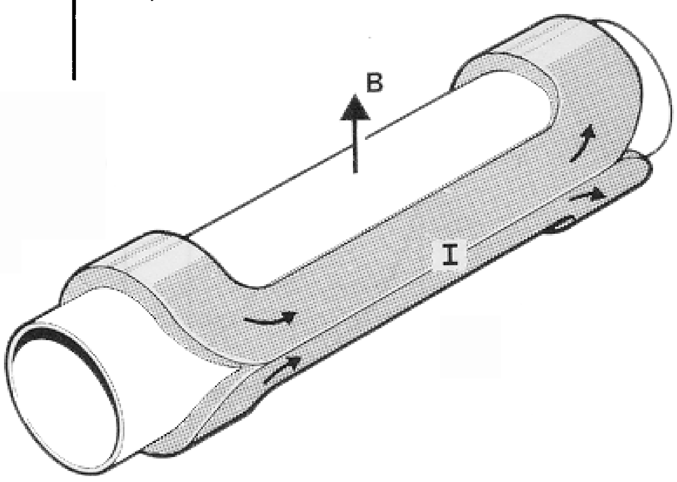
- Most superconducting particle accelerator magnets rely on saddle-shaped coils, which, in their long straight section, approximate cosθ or cos2θ distributions of the conductor



dipole



quadrupole



Saddle-shaped coil assembly for dipole magnets

Comment

- Intersecting ellipses < - > block design
- Cosθ distribution < - > cosθ design

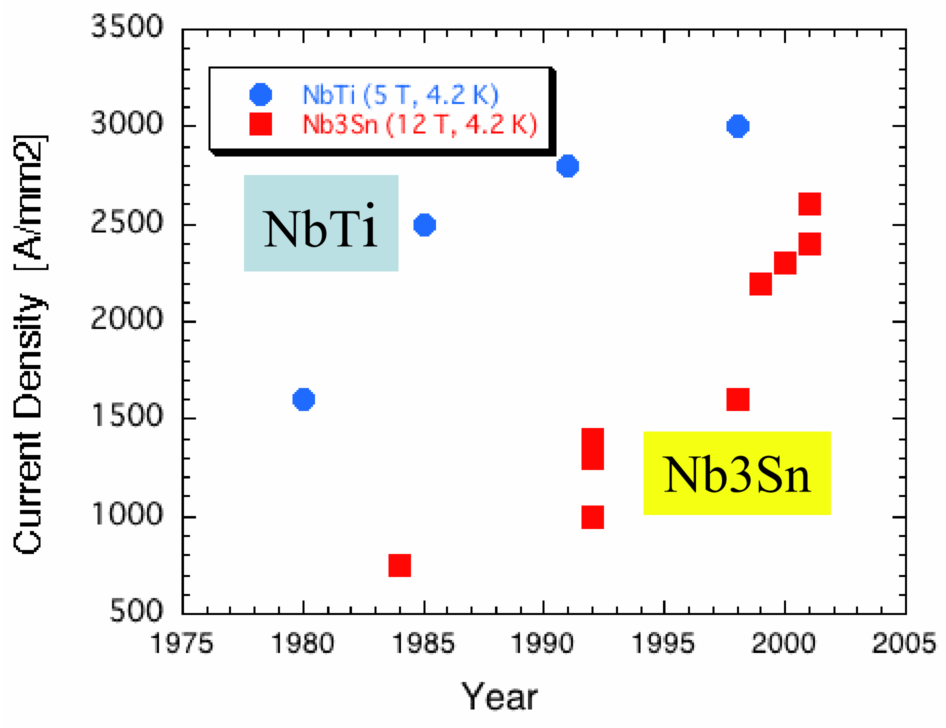
- Stress map in the block design appears to favor this geometry for very high fields and modest aperture
  - need to know

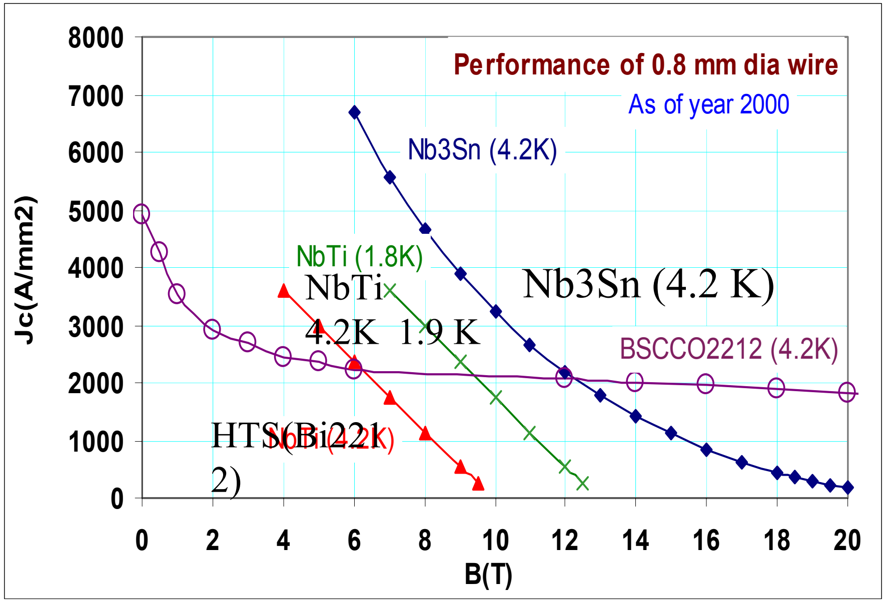
    stress sensitivity vs. background field

Status of NbTi Magnets

- Jc (NbTi) achieved
  - **~ 3 kA/mm^2** @ 5 K, 4.2 K,
- Engineering coil current density
  - **300 ~ 500 A/mm^2**
- State-of-the-art design: Cos θ and cold iron
- Magnetic field that can be reached
  - ~ 7 T at 4.2 K
  - ~ 9 T at 1.9 K (present practical limit)

Progress in NbTi and NB_3Sn Conductor for Accelerator Applications





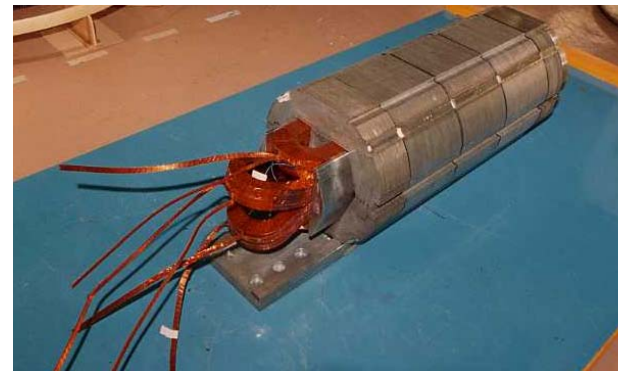
E. Barzi et al, Fermilab TD-01-013, (2001)
G. Sabbi (MT-18), M. Lamms (ASC-2002)

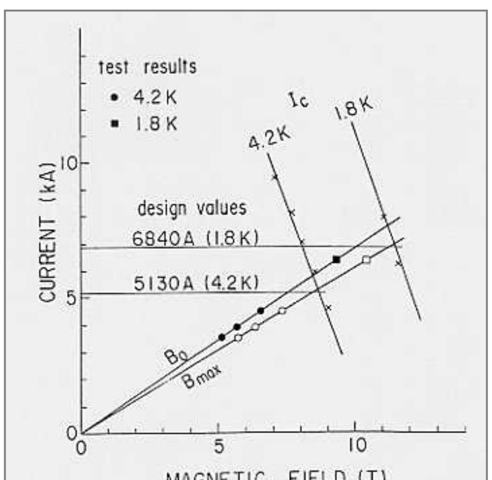
Progress in Accelerator Dipoles

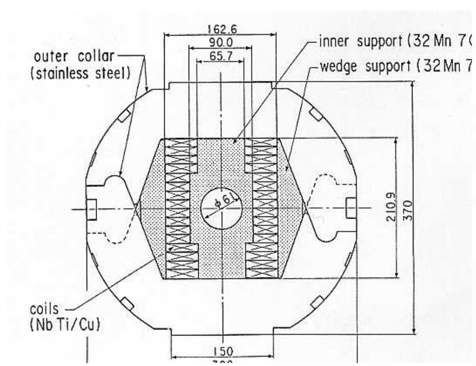
Dipole	Coil Config.	Coil Config.	Bore Field	Coil Field
RHIC	NbTi	Cos θ	3.5	4.5
Tevatron	NbTi	Cos θ	4.4	5.5
HERA	NbTi	Cos θ	4.7	5.6
Texas A&M	NbTi	Block	6.5	6.5
SSC (50 mm)	NbTi	Cos θ (50 mm)	6.6	~7
KEK (1.9 K)	**NbTi**	**Block**	**9.4**	**10.4**
KEK (1.9 K)	NbTi	Cos θ (50 mm)	10.3	
LHC (1.9 K)	NbTi	Cos θ (56 mm)	10.5	
CERN (1.9 K)	NbTi	Cos θ (56 mm)	10.1	
CERN (1.9 K)	NbTi	Cos θ (88 mm)	9.6	

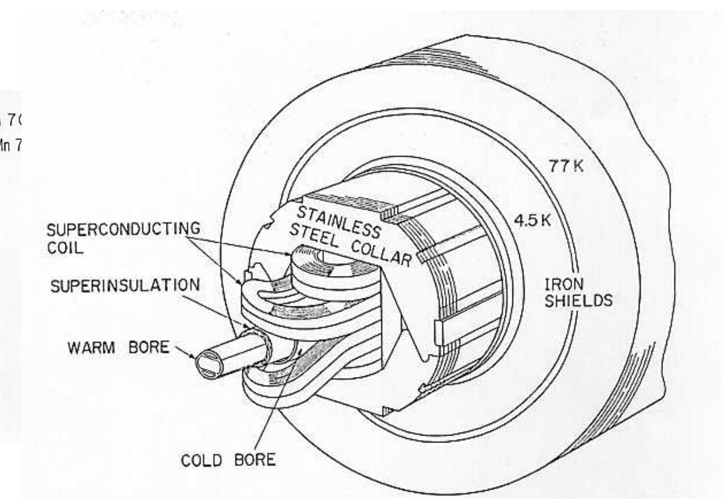
KEK NbTi Block Dipole

- Peak field 10.4 T.
- Central field 9.4 T







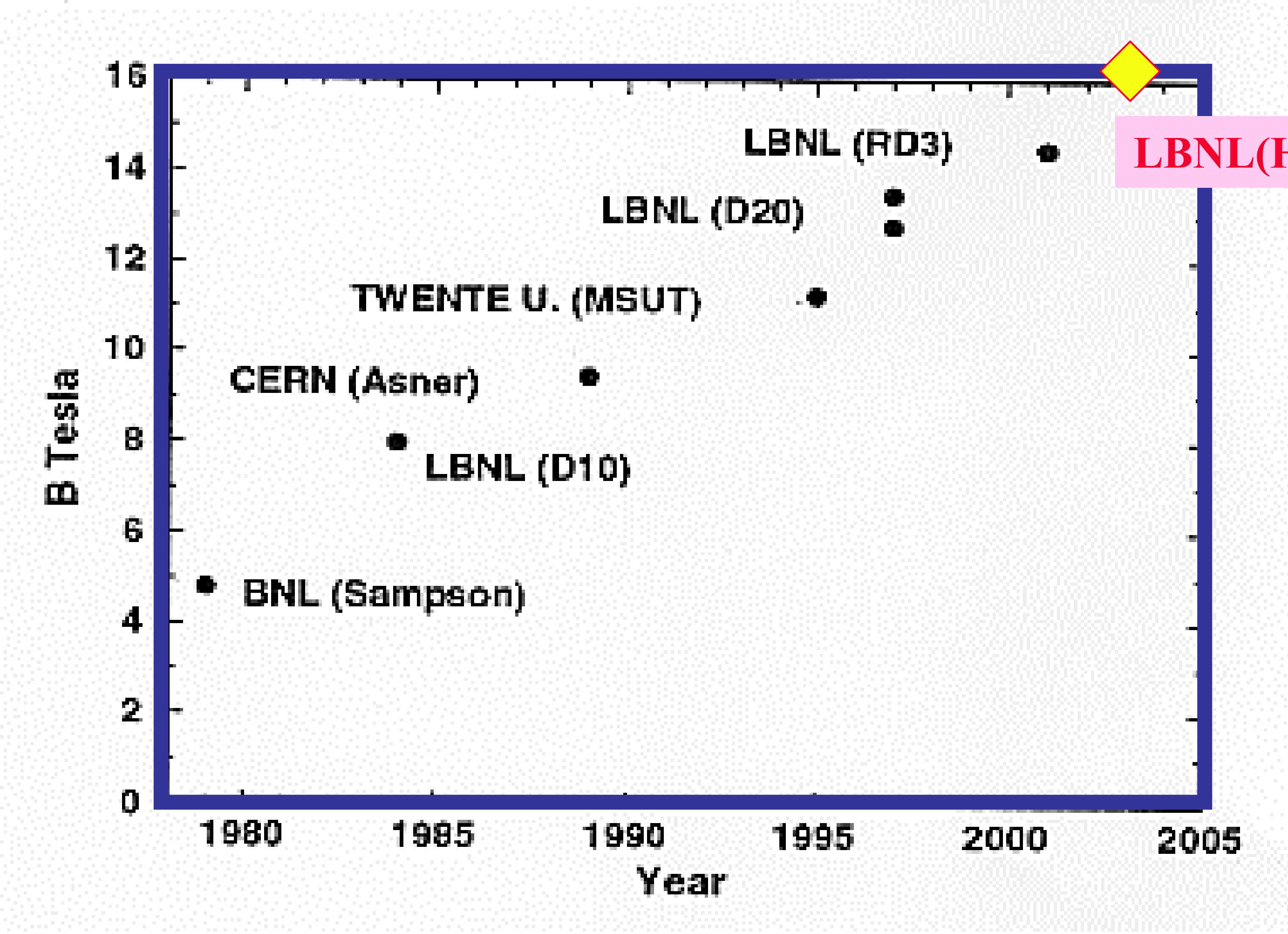


T. Shintomi, M. Wake, K. Tsuchiya, H. Hirabayashi et al., (1985)

Comment

- Block design with turned-up ends is not new

Progress of Nb_3Sn Dipoles



- R. Hafalia et al., IEEE Trans. Vol. 12, No. 1 (2002) 47 (MT-17)

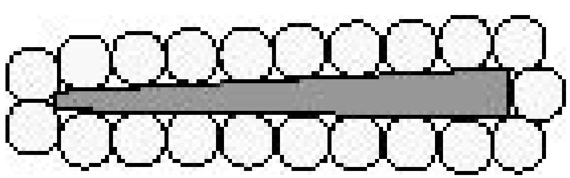
Looking to the Future

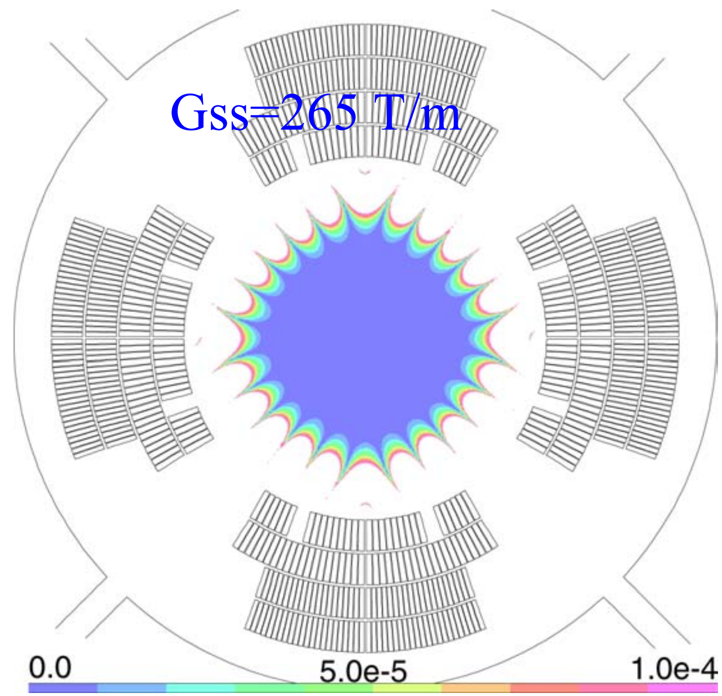
- **Nb_3Sn** magnets for
  - LHC Luminosity Upgrade
    - **Large Aperture**, high gradient **Quadrupoles**
  - Future Energy Frontier beyond LHC

- **HTS** for future possibilities,
  - High intensity machine
    - Muon colliders and neutrino factories

IRQ Upgrade Design Study at LBNL

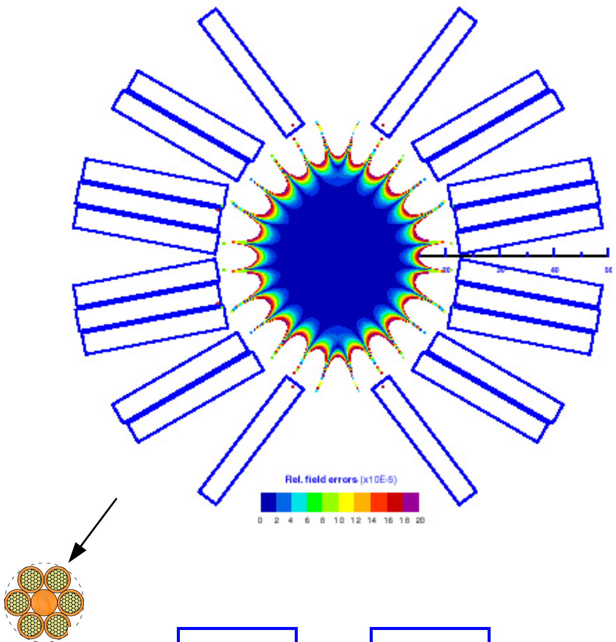
- **cos θ** design
  - 90 mm bore, 1.9 K
    - ✓Four layers – fully keystoned Nb3Sn Cable

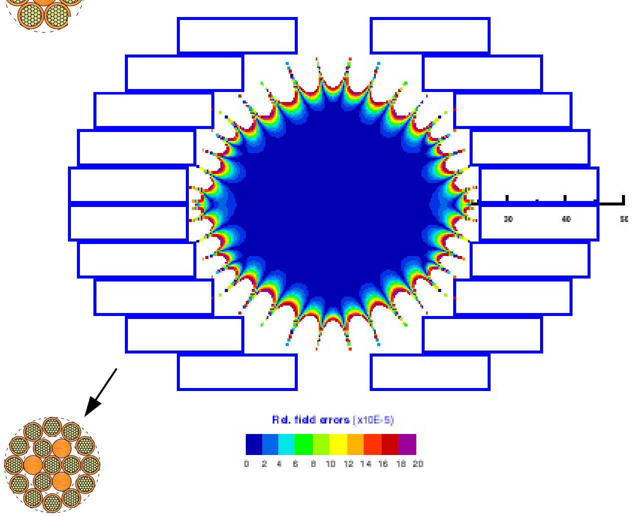




by et al., WAAP, March 2003

Why not other currents? Studies at Fermilab





Shell type dipole coil:

- **Single-layer**
- **45 mm bore with vertical ellipticity;**
- **11-12 T at Jc(12T)=3kA/mm^2**
- **90-100 kA**
- **Field quality within 10^{-5}**
- **Same coil volume as 2-layer coil**

Block type dipole coil:

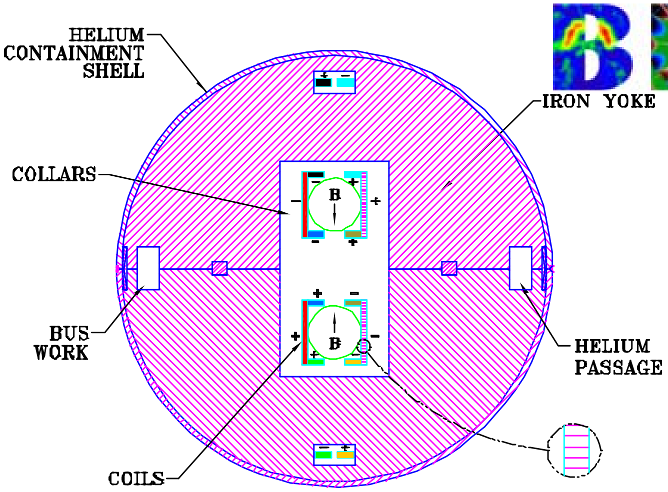
- **Single-layer design with minimum turns**
- **45 mm bore**
- **11-12 T field at Jc(12T)=3kA/mm^2**
- **100-110 kA**
- **Field quality within 10^{-5}**
- **Suitable for common coil design**

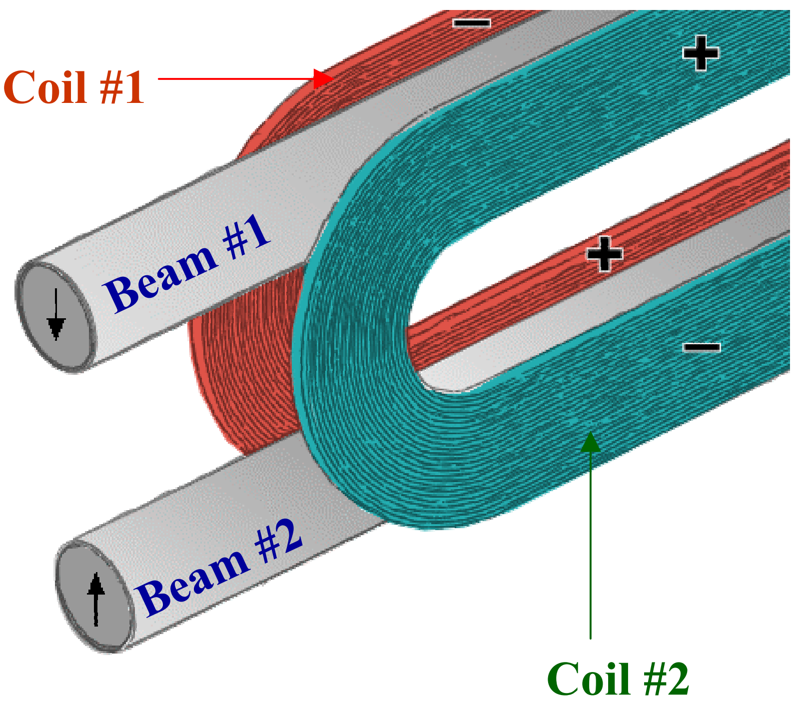
Comment

- There is no magic in 10 – 20 kA

We must not confine ourselves to this current just because the test set up suits it – the cost of a new test set up would not be excessive

Common Coil Design





Main Coils of the *Common Coil Design*

- **Simple 2-d geometry**
  - **with large bend radius**
- **Conductor friendly**
  - **no complex 3-d ends**
- **Compact**
  - **quadrupole type cross-section**
- **Block design**
  - **Simpler handling large Lorentz forces**
- **Combined function magnets**
  - **possible**
- **Efficient**
  - **Methodical R&D**
  - **Simple & modular design**
- **Minimum requirements**
  - **on expensive tooling and extensive labor**
- **Lower cost magnets expected**

Comment

- The common coil design, though elegant, does not appear to be the best for very high field
  - Side-by-side is more convenient for twin aperture
  - Forces are more difficult to handle than in side-by-side block design
  - Peak field on conductor is higher
  - Field quality is harder to obtain

Are there other ideas out there?

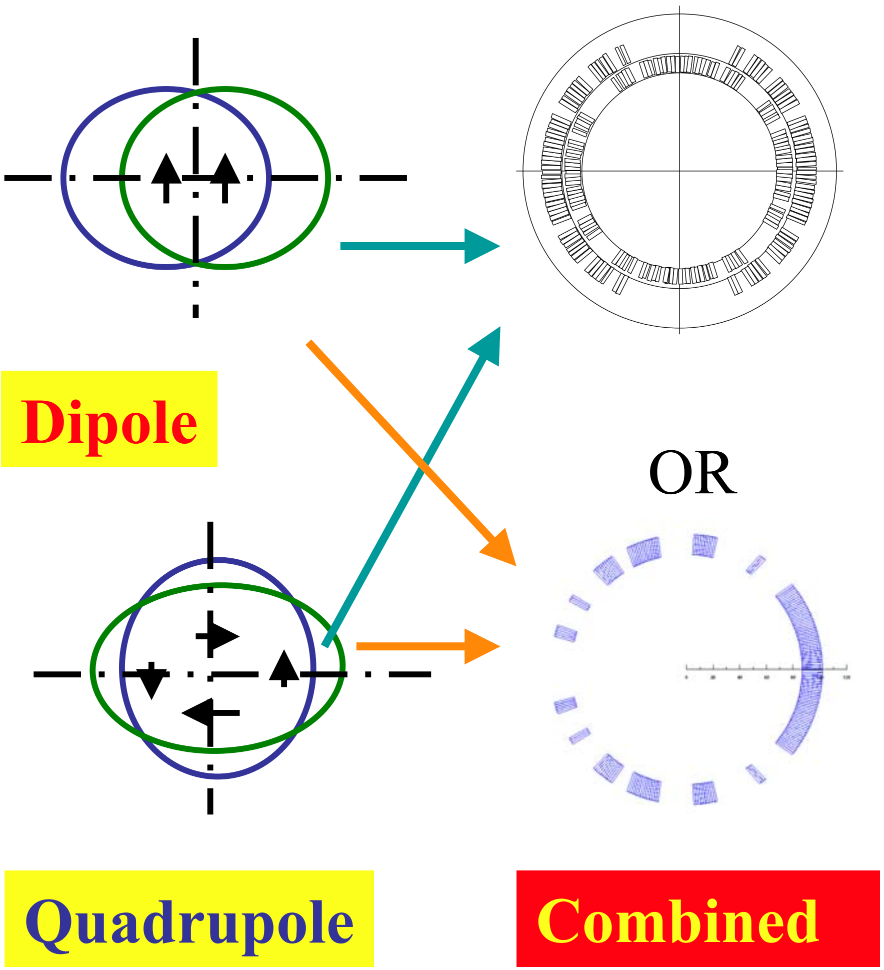
This is a unique moment in time to think outside the box

- Example: how about combined function magnets? This was studied for LHC: interesting, but too late. Idea is now applied to J-PARC superconducting beam line for neutrino experiments (KEK-JAERI)
- Can be cost effective
  – Only one type of magnet to develop
- Higher energy for given tunnel length/diameter

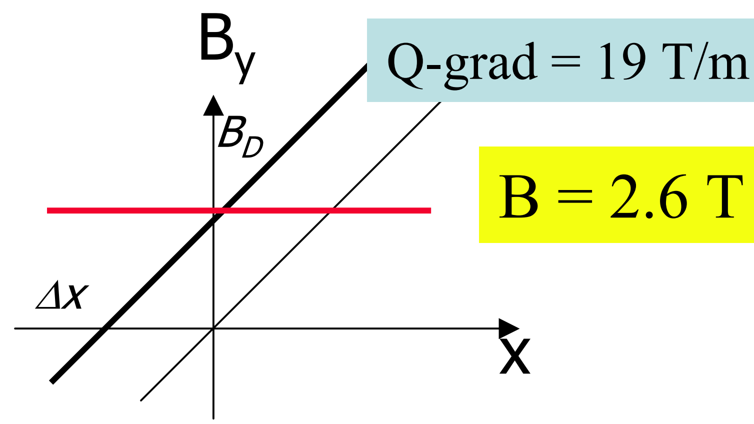
Combined Function Superconducting Magnets

- Can be cost effective
  - Only one type of magnet to develop
- Higher energy for given tunnel length/diameter
- Example: J-PARC superconducting beam line for neutrino experiments at KEK-JAERI

Concept of Combined Dipole Field with Quadrupole



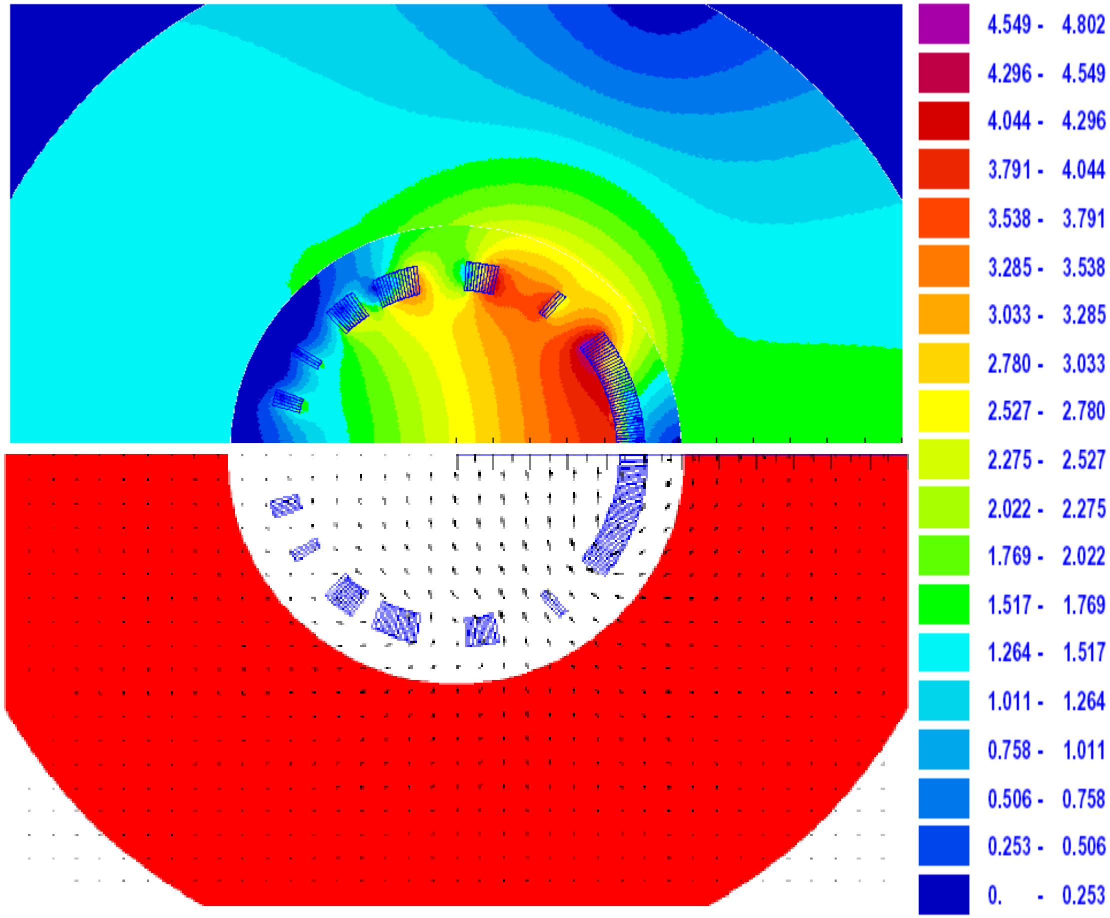
$$B_y = B_D + Q_{\mathrm{grad}} \times x$$
$$= Q_{\mathrm{grad}}(x - \Delta x)$$
$$\Delta x = -\frac{B_D}{Q_{\mathrm{grad}}}$$



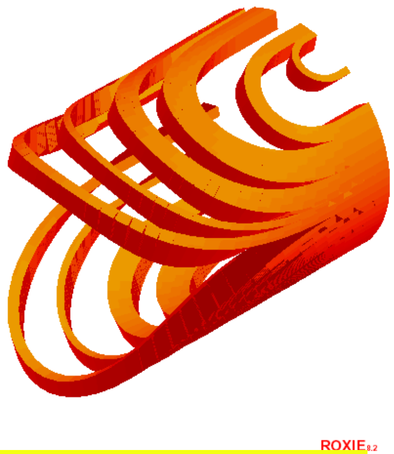
Peak Field: 4.2 T

KEK/BNL

2D & End Electromagnetic Design (ROXIE optimization)



- **B = 2.6 T**
- **G = 18.5 T/m**
- **I = ~7kA**
- **L = ~15mH**
- **Quality <10^{-3} @ 5 cm**

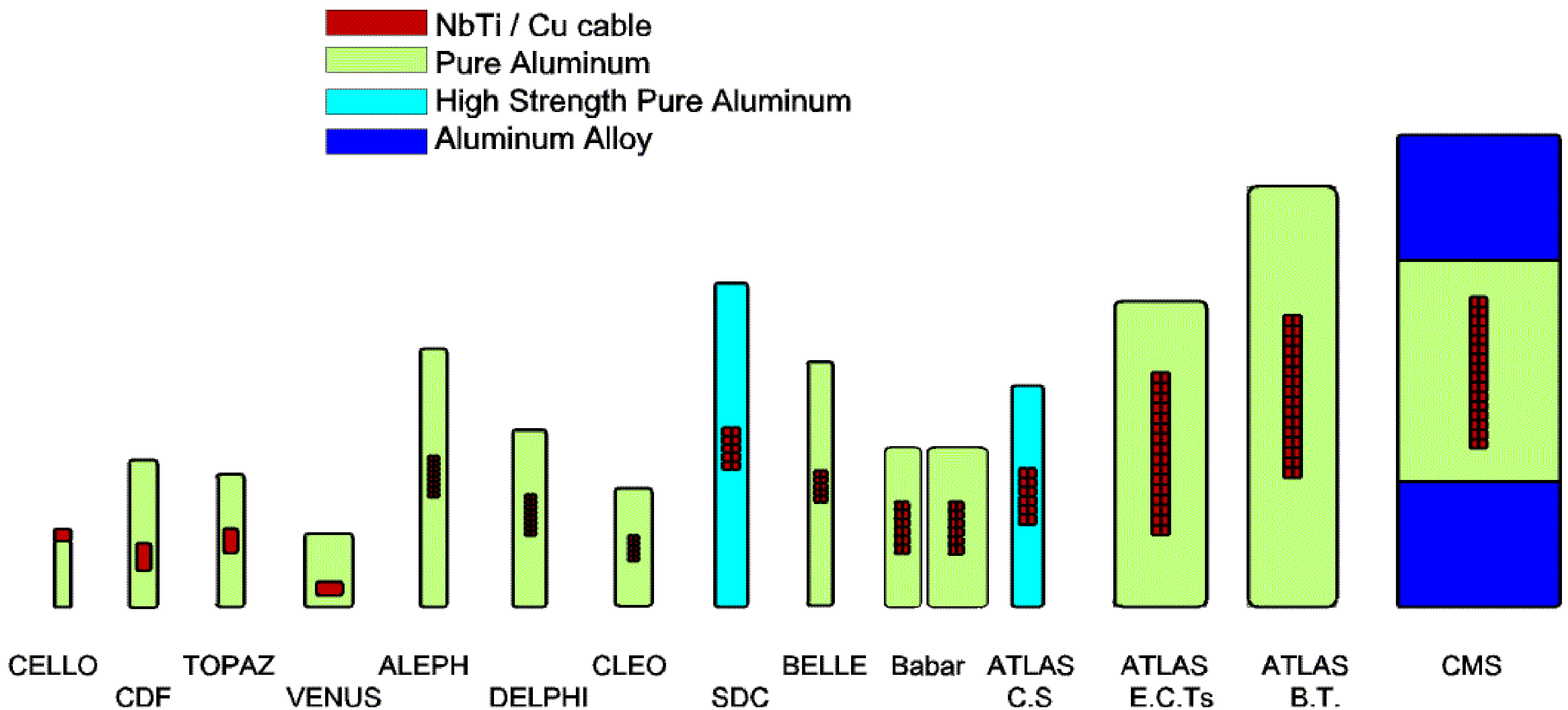


Acknowledge to ROXIE S. Russenschuck et al) to make the design possible

Can some Features of Detector Magnets be imported?

- Al-stabilized superconducting coils
- Indirect cooling, forced flow 2-phase helium or thermo-siphon cooling
- Quench propagation strips of pure Al

Progress of Al-stabilized SC



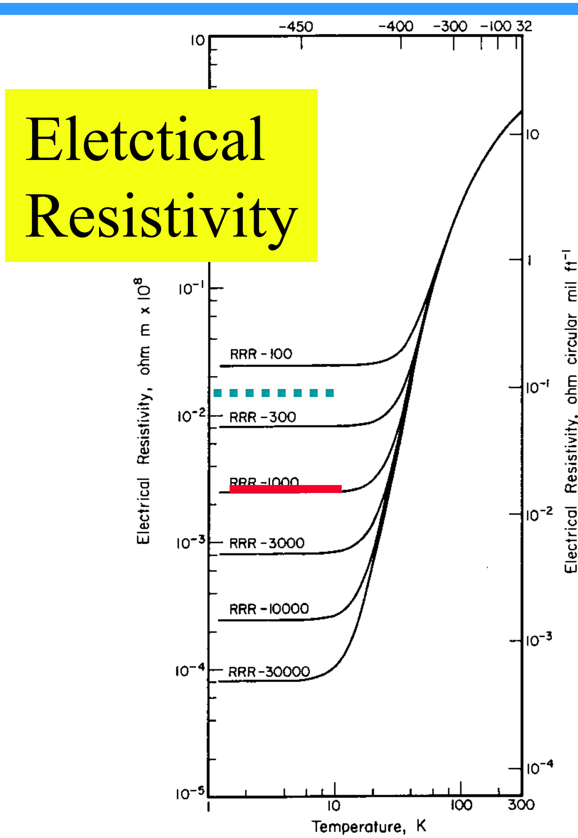
Roles of Aluminum Stabilizer

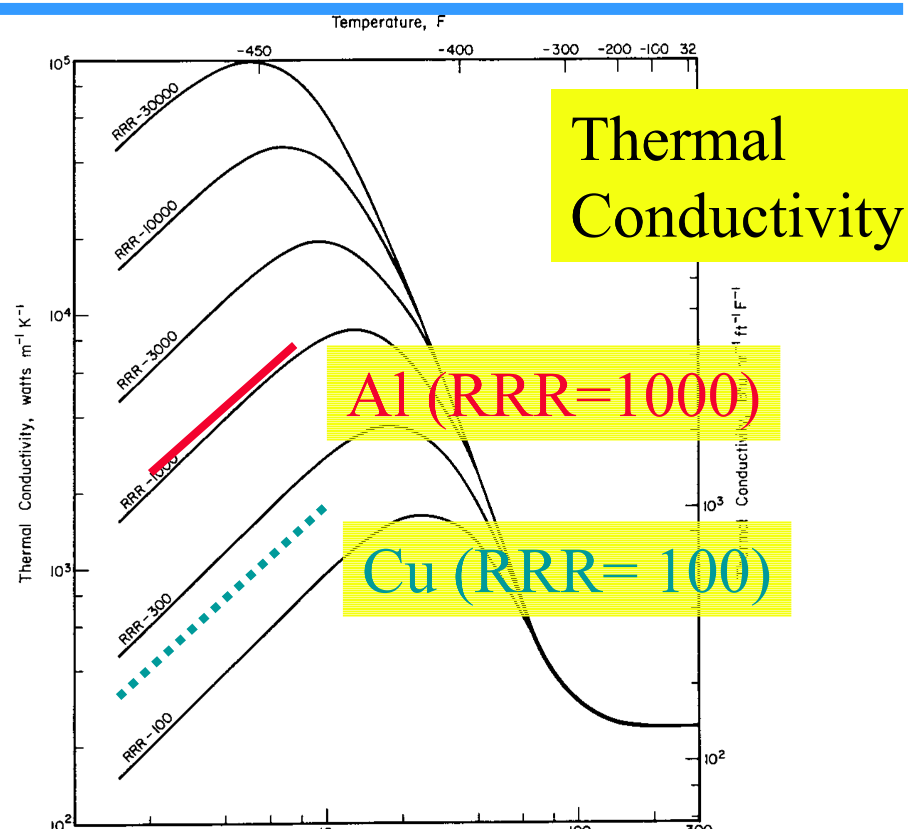
- **Stabilizer for Superconductor**
  - Low Resistivity
- **Energy absorber with Joule Heating in case of quench**
  - Large heat capacity / mass
- **Transparency / Light weight**
  - Low Z, and low density

High-Strength Aluminum Stabilizer has been developed

Can we find a use for it?

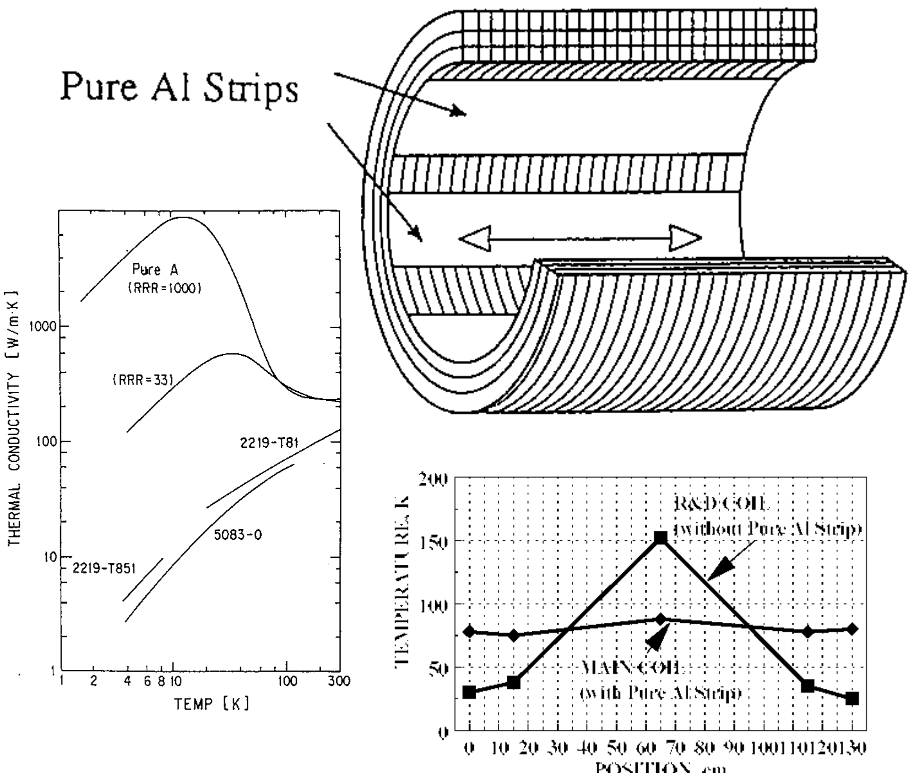
Electrical and Thermal Characteristics of Aluminum





Aluminum can provide a very wide range characteristics , depending on the purity (or RRR)

Fast Quench Propagation by using pure-Al Strips



Circumferential Velocity:

$$V\phi = (J/\gamma C)\cdot\{L_0T_s/(T_c-T_o)\}^{1/2}$$

Axial Velocity:

$$V_z = (k_z/k_\phi)^{1/2}\cdot v_\phi$$

To improve Z propagation;

Axial Pure Al-strip useful !!

Axial Pure-Al strip useful to homogenize Coil temperature

Conclusion

- NbTi Accelerator magnets @ 1.9 K well established
- Nb3Sn magnets expected for beyond 10 T
- Nb3Sn dipole has achieved > 15 T at LBNL

Future

- Is warm iron worth revisiting?
- Block vs. cos θ debate: see "stress map" in the winding…
- Why 10 – 20 kA? Why not 5 kA or 50 – 100 kA?
- Combined function design?
- Can we make use of high-strength aluminum stabilizer? (from Large Scale Detector Magnet R&D) ~200 MPa
- Can we make use of pure Al "drains" ?